n_TOF facility past and future

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Abstract
The neutron Time of Flight (n_TOF) facility at CERN is a source of high flux of neutrons obtained by the spallation process of 20 GeV/c protons onto a solid lead target and the remarkable beam intensity of the Proton Synchrotron (PS). From November 2008 the n_TOF facility resumed operation after a halt of 4 years due to radio-protection issues. It features a new lead spallation target with a more robust design, more efficient cooling, separate moderator circuit, target area ventilation and most important without any loss of the unique neutron performances of the previous target. Moreover the separate moderator circuit will permit in the future the use of borated or heavy water instead of normal water to reduce the 2.2 MeV gamma background for the neutron capture measurements. The facility has been commissioned in Nov 2008, with performances similar of the previous target and predicted by Monte Carlo simulations. The facility will resume operation for physics from May 2009 with 4 experimental proposals already approved by the Research board, on Astrophysics, Fission fragment distribution and fundamental physics with neutron-neutron scattering.

1 The n_TOF Facility

The concept of the n_TOF neutron beam [1,2] makes use of both the specifically high flux of neutrons attainable using the spallation process of 20 GeV protons on an extended lead target containing practically the whole spallation shower and the remarkable beam density of the CERN Proton Synchrotron (PS) [3]. After the initial proposal [1], in a short amount of time the facility was accepted for construction by CERN at 1999 Fig. 1. The CERN n_TOF facility has been set in operation and commissioned in 2001 with performances matching the expectations. The PS machine of CERN can generate high intensities up to 7×10^{12} ppp (protons per pulse) - high enough to produce the vast number of 2×10^{15} neutrons per pulse - in the form of short (6 ns width) pulses with a repetition time varying from 1.2 s to 16.7 s and a prompt “flash” considerably smaller compared to electron machines. The high neutron flux, the low repetition rates and the excellent energy resolution of $3\text{x}10^{-4}$ open new possibilities to high precision cross section measurements in the energy range from thermal to GeV, for stable and, moreover, for radioactive targets. During the first years of operation 2001-2004 the n_TOF collaboration has attained a rich experimental program measuring in total 40 isotopes and producing numerous scientific papers and proceedings. In 2005 the experimental program was brought to halt due to radiation protection issue with the cooling water. Several solutions have been envisaged and finally in 2008 the facility restarted its operation with a new spallation target with equal performances with the previous one.

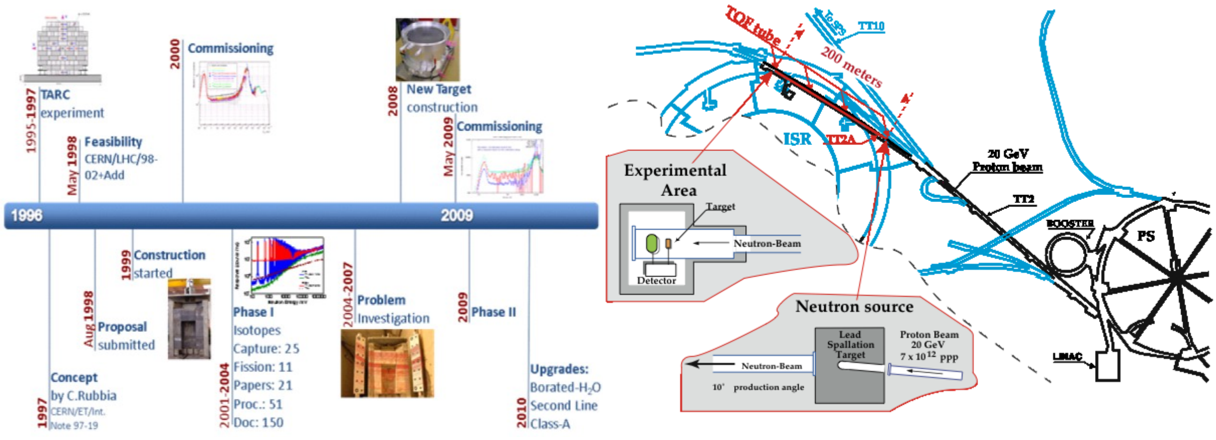

Figure 1: Timeline and layout of the CERN n_TOF facility.

2 Performances of the n_TOF facility

A series of measurements has been performed to characterize the neutron beam in the experimental area. These measurements have been performed during the commissioning phase in 2001 [4] with the PTB Ionization chambers [5], the Silicon Monitors SiMON [6], the C_6D_6 gamma-ray detectors [7], the Fast Ionization Chamber FIC and with the PPACs detectors [8]. All these measurements characterized with high accuracy the neutron beam, both in terms of neutron fluence Figure 1, but also in terms of energy resolution with the help of well known and isolated resonances of Fe at 11.2, 34.2, 80.8 and 175.9 keV.

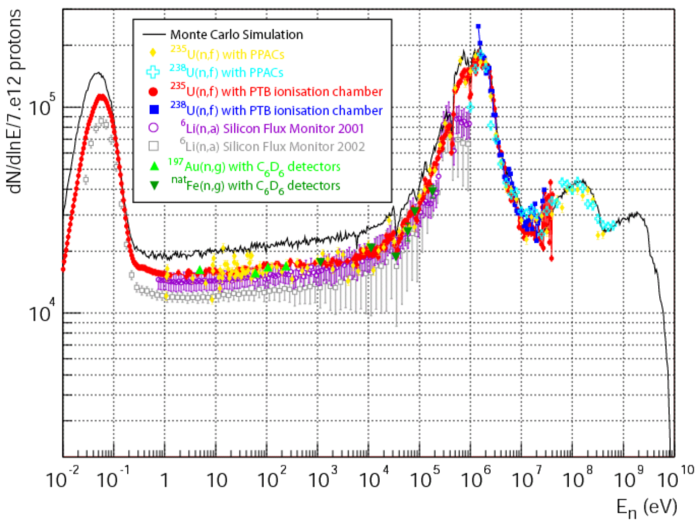

Figure 2: Neutron flux in EAR-1 as measured with different experimental techniques. A comparison is shown with the Monte Carlo simulations.

To understand better the properties of the facility an extensive simulation campaign has been performed in parallel with the measurements [9]. The detailed description of the facility and the spallation target has been modelled in various state of the art computer codes: FLUKA, EA-MC, and MCNP/X. All the simulations showed consistent results between them and with the measured data, within 15%, well below the margin of error that one can accept from such a complicated simulation setup.

Different forms of shielding have been devised and the geometry of the experimental area has been optimized in order to keep the background to a level compatible with the operation of large calorimeters. The program of measurements for determining the background level in the measuring station confirmed the results of the simulation studies. Showing that the dominant component is the neutrons arriving through the beam pipe, and scattering on the samples under study representing the most significant background.

3 n_TOF experimental apparatus

During the period 2001-2004, the n_TOF Collaboration has setup all the necessary infrastructure for neutron cross section measurements in the present n_TOF experimental area [10]. These include neutron flux monitors, capture γ-ray detectors, fission detectors and a high-performance data acquisition system based on fast FADC (flash analogue-to-digital converters).

3.1 The innovative data acquisition system at n_TOF

The high instantaneous neutron flux at n_TOF, represents a great advantage especially for the measurements of small mass and radioactive samples as in our case but it poses relevant problems on signal processing and acquisition due respectively to pile-up events and large dead times. To overcome those problems, an innovative data acquisition (DAQ) system based on fast digitizers has been set-up [11]. The main feature of this system consists in the possibility to sample and record the full analogue waveform of the detector signal. The sampling is performed by means of fast Flash Analogue to Digital Converter (FADC), with sampling rates up to 1 Giga Samples/s.

3.2 Capture detectors

For neutron capture cross section measurements at a neutron time-of-flight facility such as n_TOF, the detection of γ-ray following a capture event can be done with two different techniques. A technique in which one γ-ray per capture event is detected has been used at n_TOF and it is based on C6D6 liquid scintillator detectors. A different approach is to use a detection system in which the full γ-ray cascade is detected for each capture event. In this case it is fundamental to record the γ-rays with high detection efficiency, ideally 100%.

The n_TOF TAC is based on BaF2 crystals. It is an array of 40 modules which covers 95% of the 4π solid angle (Fig.3). The detection efficiency (when used in calorimeter mode) is of the order of 99%. With the high efficiency of the n_TOF TAC it has been possible to measure samples with low mass (hence, with relatively low intrinsic activity for radioactive species).

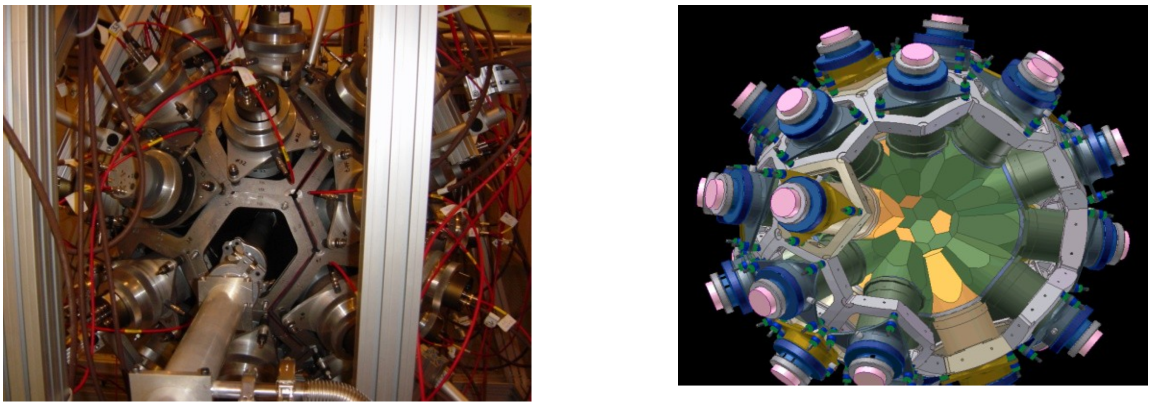

Figure 3: Schematic view of the Total Absorption Calorimeter (TAC).

3.3 Fission detectors

Two fission detectors have been constructed for the n_TOF experimental campaign:

The Parallel Plate Avalanche Chamber (PPAC) consisting of two twin parallel stretched foils with a very low gas pressure in between, operating with the same principles as a multi-wire proportional chamber. The targets are deposited on 2 μm aluminium foils, which are thin enough to allow the coincident detection of the fission fragments. On both sides of each target two 20×20 cm^2 PPACs are used for detecting the fission fragments and to measure their position of origin.

Fast Ionization Chambers (FIC): The FIC chambers were essentially dedicated to the measurement of samples with relatively highly radioactive samples ^{233}U, ^{241,243}Am and ^{245}Cm and is qualified as "sealed source" according with the international standard ISO 2919. The fission-fragment events are recognized by simple amplitude discrimination with efficiency very close to 100%, limited only by the fission-fragments absorption in the target itself. With a deposit density of ~150 μg/cm^2 the measured efficiency in FIC is 95%. The working conditions of the detector have been optimized by means of FLUKA simulations and a series of custom made programs to emulate the effect of the complete experimental apparatus including the electronics. The simulations were performed for the "worst" case of ^{241}Am, with a half-life of 433 yr and an alpha activity over 4π of 1.27×10^8 Bq/mg.

4 The experimental campaigns in 2002, 2003 and 2004

The measurements so far performed at n_TOF have covered capture and fission cross section measurements on a large number of samples. The full list is given in the Table I. Most of the measurements have been performed for the n_TOF-ND-ADS Project, within the EC FP5 initiative. The motivations and physics cases of the various measurements have been given in great details in the proposal for measurements submitted to the CERN INTC Committee [12-20]. Here we will show the results of a few of the measurements performed.

Capture	Fission
^{151}Sm, ^{204,206,207,208}Pb ^{209}Bi, *^{232}Th,* ^{139}La ^{24,25,26}Mg ^{90,91,92,93,94,96}*Zr* ^{186,187,188}Os, *^{240}Pu* *^{233,234}U, ^{237}Np,* *^{243}Am*	*^{233,234,236}U* *^{232}Th* *^{237}Np* *^{241,243}Am* *^{245}Cm*
^{197}Au	*^{235,238}U*

Table I: Measurements of capture and fission cross sections performed at CERN n_TOF during the 2002, 2003 and 2004 experimental campaigns.

4.1 The ^{151}Sm(n,γ) cross section measurement

This cross section is important in nuclear astrophysics because ^{151}Sm is a branching point in the s-process path. In particular, this branching is sensitive to the temperature at which the s-process nucleosynthesis is taking place. The accurate determination of the neutron capture cross section of ^{151}Sm can thus provide crucial information on thermodynamics conditions in AGB stars.

The measurement at n_TOF [21] has been performed with an enriched ^{151}Sm sample provided by ORNL (Oak Ridge National Laboratory). The 200 mg of ^{151}Sm encapsulated in a 0.1 mm thick Ti-can induces 200 GBq (5.3 Ci) activity. With such a large activity this kind of measurement is hardly possible at other white neutron time-of-flight facilities. The measurement has been performed with a set of C6D6-based liquid scintillator detectors specifically-designed for low neutron sensitivity.

The result obtained at n_TOF is $<\sigma(n,\gamma)> = 3100 \pm 160$ mb, a value much larger than previous estimates, all based on model calculations, which ranged from 1500 to 2800 mb. The firm estimate of the capture rate for the first time based on an experimental value allowed reaching two important conclusions with respect o the s-process nucleosynthesis in this mass region:

- the classical model, based on a phenomenological study of the s process fails to produce consistent results of the branching at ^{151}Sm and ^{147}Pm.
- the p-process contribution to the production of 152Gd can amount up to 30% of the solar-system observed abundance.

A detailed description of these results is given in n_TOF publications [17].

4.2 Measurement of the fission cross section of Actinides

Three experimental campaigns devoted to fission cross section measurements have been performed so far at n_TOF. Two different setups have been used for the detection of fission events induced by neutron interaction, one based on a Fission Ionization Chamber (FIC) and the other based on Parallel Plate Avalanche Counters (PPAC). The list of isotopes measured includes $^{233,234,236}U$, ^{232}Th, ^{237}Np, $^{241,243}Am$, and ^{245}Cm.

We are presenting an example of fission data, to give a flavour of the capabilities of high precision fission cross section measurements at n_TOF. The example shown is the result of the $^{236}U(n,f)$ cross section measurement performed at n_TOF in 2003 with the FIC detector. In comparison with the previous measurement from the Pommard nuclear explosion [22], the n_TOF resolution is much superior. In the energy range shown, a triplet of resonances could be discriminated while in the previous data a unique bump was visible.

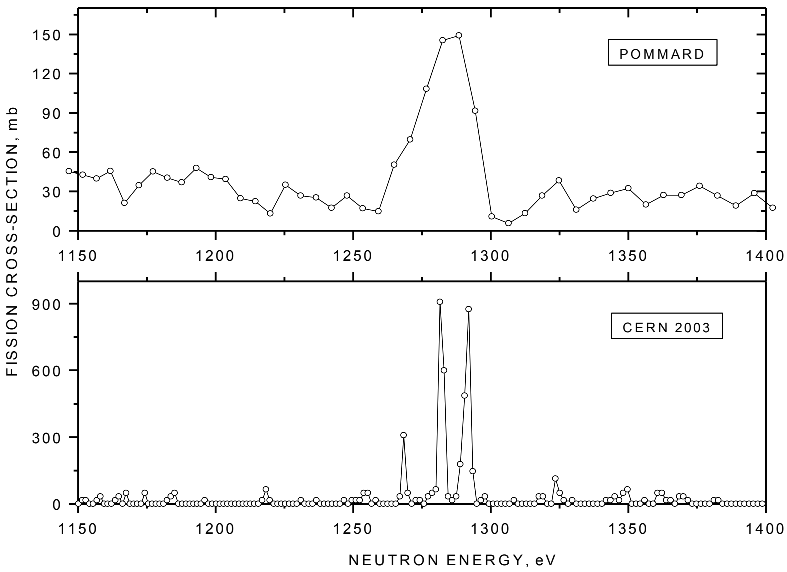

Figure 4: A comparison of the $^{236}U(n,f)$ with previous measurements.

Once again, as for capture cross section measurements, the superior performances of the n_TOF facility, in combination with the high-performance experimental apparatus has been able to provide nuclear data of high accuracy.

5 Facility Restart

Following a complete halt of the experimental activities in 2004 due to radioprotection problem with the cooling of the lead target, several options were investigated for the design of a new spallation target. Finally the adopted solution was to use, as in the first time a lead target inside an aluminium vessel with direct contact with demineralised water. In contrast with the first target we tried to optimize the cooling on the critical areas and to avoid any contact with stainless steel. Figure 5 shows the conceptual design of the new target. After the approval of the new design the construction was completed in less than 6 months and in Nov 2008 the n_TOF facility was ready for operation.

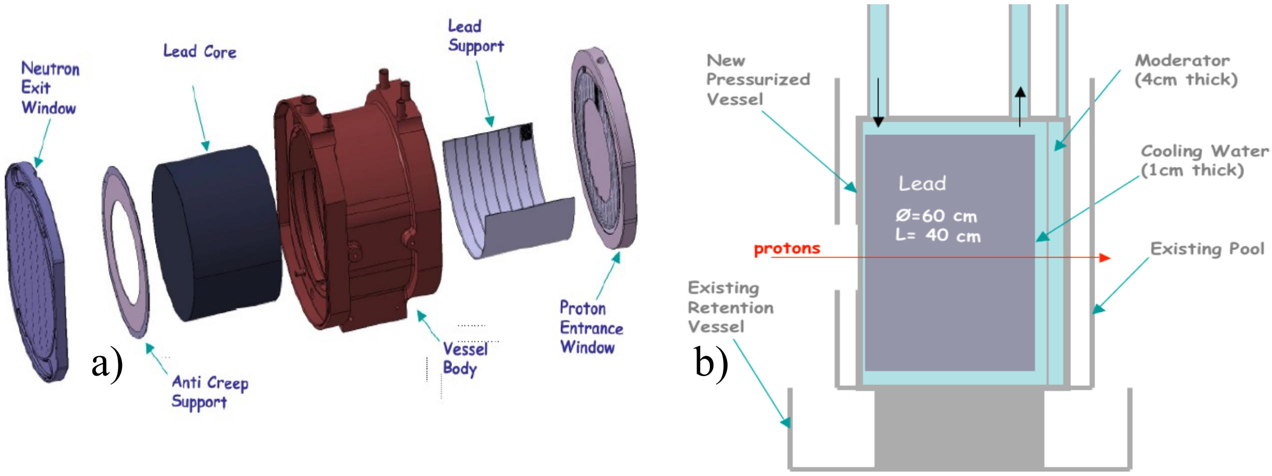

Figure 5: The conceptual design of the new Lead target a) View of the different part of the lead target b) schematic view of the lead target placed inside the cooling system. The cooling water is separated with Aluminium foil.

6 Final Remarks

The new Lead target has been designed and fabricated for the n_TOF facility. In addition of the FLUKA simulations, the conceptual design has helped from the experience gained from the previous target help us on the construction of the new Lead target for the n_TOF facility at CERN. The commissioning performed in spring 2009, showed that the values are consistent with the expectations and equivalent with the performances of the previous target, analysis work is still in progress. After the commissioning planed for the determination of the new characteristic and performance of the updated n_TOF facility a new campaign of measurements will be performed. The following proposals have already been accepted by the CERN Research Board:
- "*The role of Fe and Ni for s-process nucleosynthesis in the early Universe and for innovative nuclear technologies*" (CERN-INTC-2006-012);
- "*Proposed study of the neutron-neutron interaction at the CERN n_TOF facility*" (CERN-INTC-2006-006);
- "*Angular distributions in the neutron-induced fission of actinides*" CERN-INTC-2006-016;
- "*n_TOF: New target commissioning and beam characterization*" (CERN-INTC-2008-035).

Currently we are working on various possible upgrades to enhance the performances as well to make the use of highly radioactive targets in the experimental area easier, with no constraints of the detector bodies. These are:

- The use of Borated water as neutron moderator. Boron-10 has a high neutron cross section absorbing the thermal neutrons before they are captures by Hydrogen in the water which emits the prompt gamma of 2.2 MeV transition from Deuterium. This enhancement will strongly reduce the in-beam gammas in the region of keV.
- Characterise the experimental area as a Work Sector of Type A. This will allow the use highly radioactive samples in the experimental area with no restriction from the radioprotection authorities.
- Construction of a second beam line, a vertical flight path of 20 m which will strongly enhance the neutron fluence for measurements of a target, where only tiny quantities are available.

In total CERN n_TOF has proven to be a unique facility in the world for its performances and also of the rich scientific program that has been performed, produced numerous publications and valuable data in the field of nuclear physics. A similar strength experimental program is foreseen for the near future.

Capture measurements	
Mo, Ru, Pd stable isotopes	r-process residuals calculation isotopic patterns in SiC grain
Fe, Ni, Zn, and Se (stable isotopes), ^{79}Se	s-process nucleosynthesis in massive stars accurate nuclear data needs for structural materials
A≈150 (isotopes varii)	s-process branching points long-lived fission products
^{234,236}U, ^{231,233}Pa	Th/U nuclear fuel cycle
^{235,238}U	standards, conventional U/Pu fuel cycle
^{239,240,242}Pu, ^{241,243}Am, ^{245}Cm	incineration of minor actinides
Fission Measurements	
MA	ADS, high-burnup, GEN-IV reactors
^{235}U(n,f) with p(n,p’)	new ^{235}U(n,f) cross section standard
^{234}U(n,f)	study of vibrational resonances at the fission barrier
Other measurements	
^{147}Sm(n,a), ^{67}Zn(n,a), ^{99}Ru(n,a), ^{58}Ni(n,p), other (n,lcp)	p-process studies, gas production in structural materials
Al, V, Cr, Zr, Th, ^{238}U(n,lcp)	structural and fuel material for ADS and other advanced nuclear reactors
He, Ne, Ar, Xe	low-energy nuclear recoils (development of gas detectors)
n+D_2	neutron-neutron scattering length

Table II: Proposed n_TOF Phase II experimental program.

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